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Special Issue: New Stellarators

This is a very exciting time for the international stellarator community — a new generation of advanced stellarators is being built throughout the world. A striking feature of this effort is the coordination and cooperation among the various national programs. Each stellarator that is being built has a significant and unique role to play in the international program.

- The Large Helical Device (LHD) in Toki, Japan, will explore the merits of an advanced helical coil design.
- Wendelstein 7-X (W7-X) in Greifswald, Germany, is an advanced stellarator that uses modular coils to reduce the plasma currents and improve transport.
- The Helias Stellarator Experiment (HSX) in Madison, Wisconsin, is a small modular stellarator that has been optimized to test the principle of quasi-helical transport.
- TJ-II in Madrid, Spain, is a flexible heliac that can explore the regimes of high rotational transform and highly modulated plasma shapes.

Both LHD and W7-X will use superconducting coils. Because no plasma current drive is required in stellarators, they will be the first toroidal fusion machines that can explore truly long pulse issues.

This special issue is devoted to these new stellarators. I have asked the contributors to concentrate on the engineering and construction aspects of the devices because their physics properties have been covered in detail in previous issues of *Stellarator News*.

Stellarator News is now available electronically (in color) in Adobe Acrobat (PDF) format on the Los Alamos Physics web server (*http://xxx.lanl.gov/plasm-ph*). Free Acrobat readers may be obtained from the Adobe web server (*http://www.adobe.com*).

In this issue . . .

Construction status of LHD

This year (1995) is the sixth year of the eight-year construction period of the Large Helical Device (LHD) project. The National Institute for Fusion Science (NIFS) expects the construction to be finished during 1997. The research and development program (R&D), the machine design and its construction have been performed satisfactory according to the established LHD construction schedule. A recent sign of progress is that on-site construction has been started for the superconducting helical coils, the largest poloidal coils, supporting structure, and other major components of the LHD device. We have already overcome the the major hurdles of the tight and long construction schedule of the LHD project.

The LHD is a superconducting (SC) toroidal fusion apparatus that has a maximum stored energy of 1.6 GJ. It is a heliotron-type device and has l = 2 continuous helical coils and three sets of poloidal coils, which are all SC. The specification and a bird's- eye view are shown in Table 1 and Fig. 1.

Table 1. Specifications of LHD

	PHASE I	PHASE II
MAJOR RADIUS	3.9 m	←
COIL MINOR RADIUS	0.975 m	←
AVERAGED PLASMA RADIUS	0.5 ~ 0.65 m	←
PLASMA ASPECT RATIO	6 ~ 7	←
ℓ	2	←
m	10	←
$\gamma_c = m/2 \cdot a_c/R$ (PITCH PARAM.)	1.25	←
α (PITCH MODULATION FACTOR)	0.1	←
MAGNETIC FIELD		
CENTER	3 T	4 T
COIL SURFACE	6.9 T	9.2 T
HELICAL COIL CURRENT	5.85 MA	7.8 MA
COIL CURRENT DENSITY	40 A/mm^2	53 A/mm^2
NUMBER OF LAYERS	3	←
LHe TEMPERATURE	4.4 K	1.8 K
POLOIDAL COIL CURRENT	STEADY	REAL TIME
INNER VERTICAL COIL	5.0 MA	←
INNER SHAPING COIL	-4.5 MA	←
OUTER VERTICAL COIL	-4.5 MA	←
LHe TEMPERATURE	4.5 K	4.5 K
PLASMA VOLUME	20 ~ 30 m^3	←
ROTATIONAL TRANSFORM		
CENTER	< 0.5	←
BOUNDARY	~ 1	←
HELICAL RIPPLE AT SURFACE	0.2	←
PLASMA DURATION	10 s	←
REPETITION TIME	5 min	←
HEATING POWER		
ECRH	10 MW	←
NBI	15 MW	20 MW
ICRF	3 MW	9 MW
STEADY	-----	3 MW
$D^\circ \rightarrow D^+$	-----	PRACTICE
NEUTRON YIELD	-----	2.4×10^{17} n/shot
COIL ENERGY	0.9 GJ	1.6 GJ
REFRIGERATION POWER	9 kW	~ 15 kW

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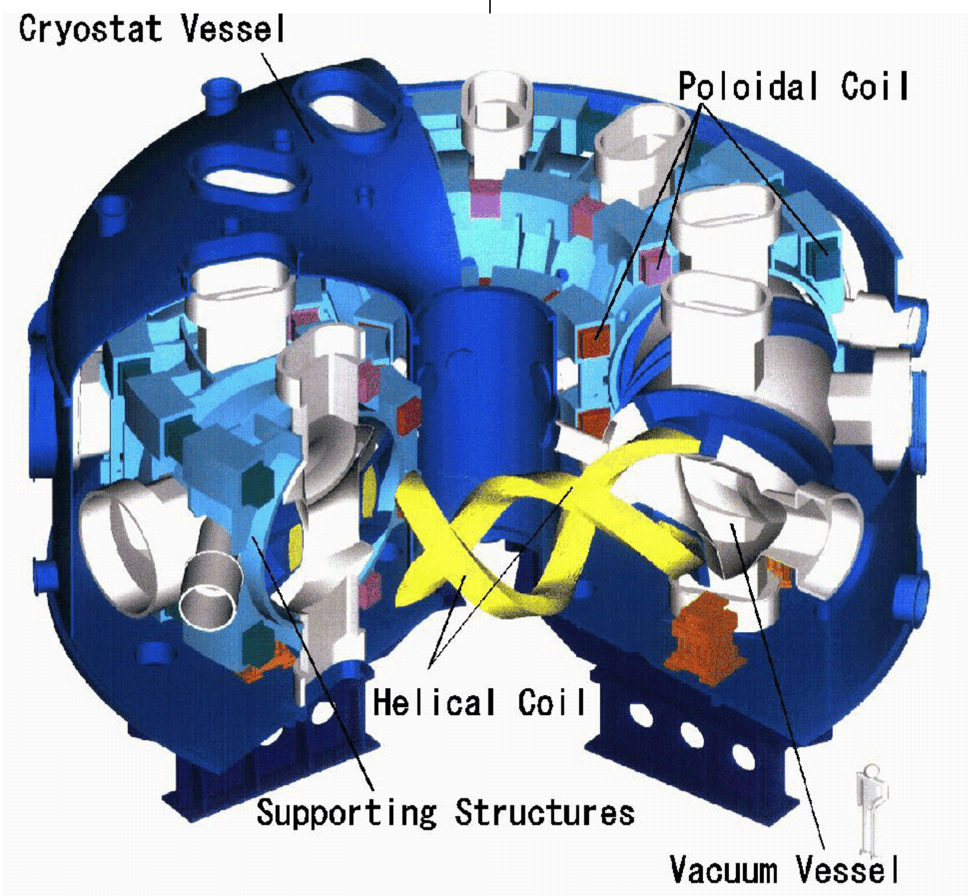

Fig. 1. A bird's-eye view of LHD showing the major components.

The major goal of the LHD project is to demonstrate the high potential of a helical device by producing current-less, disruption-free, steady-state plasmas with a large Lawson parameter. The expected performance of the LHD steady plasma is shown in Fig. 2 along with data points obtained by existing tokamaks and other helical devices.

According to the construction schedule (Fig. 3), the necessary design and R&D tasks on the SC, high heat flux components (HHFC) and divertor-related subjects should have been completed before beginning the present day on-site construction process. This R&D has been developed in cooperation with researchers at universities and the engineers of the industrial fabricators.

The utilization of the steady-state operation requires a large number of engineering innovations for the SC magnets, HHFC, heating equipment, and long-term plasma control. In particular, the development of SC magnet technology has lead to important progress, and LHD is now recognized as the largest ongoing fusion research program in the world together with the international ITER project.

During the design tasks, major critical issues arose in the design of several important components:

- superconductor cable,
- coil package installation including insulation technique,
- supporting structure and its fabrication by welding,
- cryostat,
- cryogenic system and cooldown scenario,
- coil protection,
- machine diagnostics,
- plasma vacuum chamber,
- first wall and HHFC,
- control system, and
- power supply.

Because of our intensive SC magnet R&D and design efforts, the expected performance of LHD as a steady-state superconducting fusion device has been dramatically improved.

Since 1989, we have been performing the necessary R&D to develop the NbTi fully stabilized pool-boiling-superconductor for the helical coil and NbTi forced-flow-cooled cable-in-conduit (CIC) conductor for the poloidal coil. For this R&D, we have built the necessary superconducting coil test facilities, which include a 75-kA current supply, a helium refrigerator/liquefier, a 9-T split coil, and a 1,000-ton mechanical testing machine. In 1993, we finally succeeded in developing

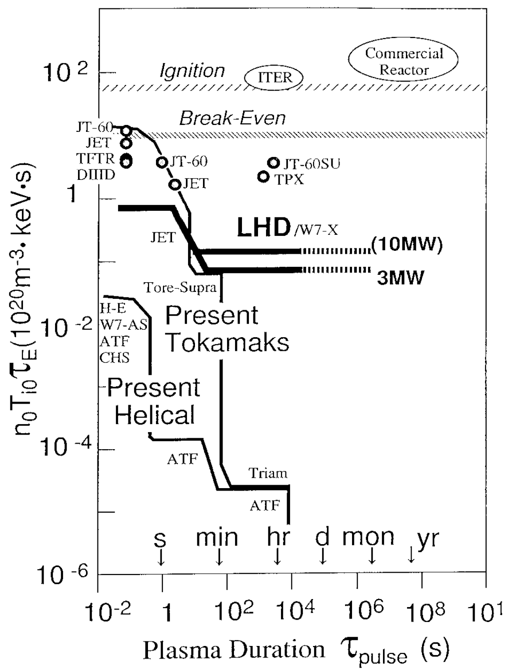

Fig. 2. Expected performance of LHD in relation to other fusion devices.

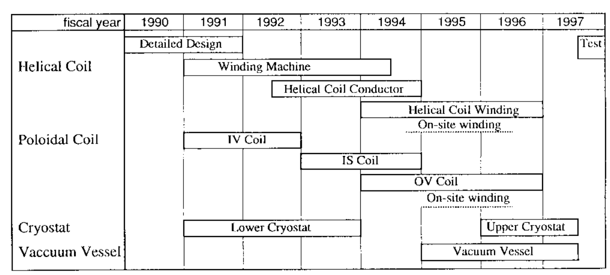

Fig. 3. Construction schedule for LHD.

the SC cable which satisfied the required specifications for the LHD helical coils and poloidal coils.

The number of major components now under construction or completed is rapidly increasing as is shown in Fig. 3:

- poloidal coils — inner vertical (1992) and inner shaping (1994),
- lower half of cryostat (1994),
- helical coil fabrication machine (1994),
- helical coil conductor (1995),
- liquid helium refrigerator (1994),
- poloidal coil power supply (1994), and
- water cooling system (1994).

The year indicated in the bracket is the scheduled time of completion. These major components have been fabricated as several separated sections in the factories of the fabricators. They have been gradually transferred to the institute since the completion of the main experimental hall building in summer 1994 at Toki site (Toki city, Gifu prefecture). Figure 4 shows an aerial view of the site. The large building is the main experimental hall, which is also shown in Fig. 5. Upon receiving the shipments from the fabricators, we have started the on-site fabrication for the major components: (1) helical coil and coil can, (2) largest poloidal coil, (3) vacuum chamber, (4) cryostat, (5) supporting structure, (6) cryogenic shield and system, and (7) machine assembly. The present status of the construction is well summarized in Table 2.

To make it possible to perform the hard on-site construction of the helical coils, a special winding machine was manufactured; its development was a big issue for our R&D to obtain the < 2-mm position accuracy of coils. The winding machine has explored a new technology area possibly called fusion mechanics. It is a numerically-controlled, huge and precision machine making the site fabrication, reliable, rapid, and therefore possible. The height, diameter, and total weight are 10 m, 13.1 m, and 280 ton, respectively. The winding machine is shown in Fig. 6. The helical coil shaping head

Table 2. Progress on each of the major LHD components.

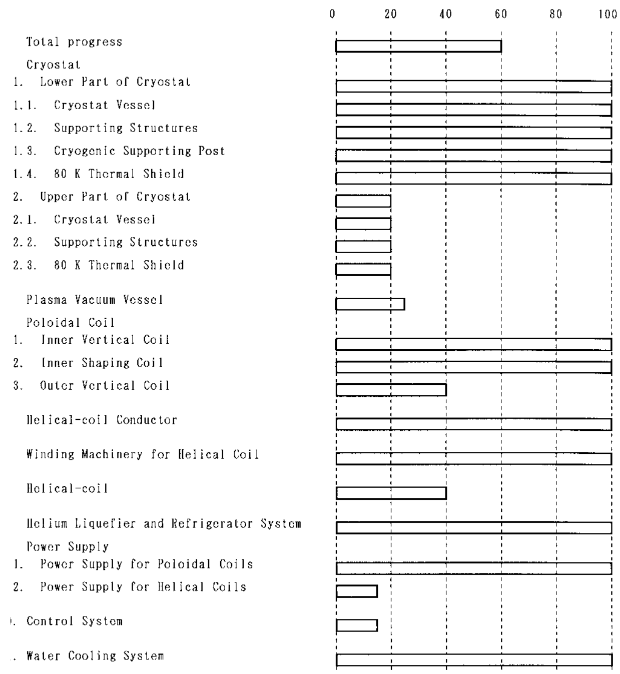

Fig. 4. An aerial view of the Toki site for LHD showing the large main experimental hall and other facilities.

rotates at the maximum speed of 0.1 rpm. This head can bend and twist the helical coil conductor with the curvature and twisting rate of 3 to 7×10^{-4} mm^{-1}, and 7×10^{-4} rad/mm, respectively. A summary of the requirements for the helical coil winding is shown in Table 3. To get the accuracy high enough to guarantee coil stability for 4-T operation in a steady-state fusion experimental device, remarkably high accuracy is required. The criterion of the allotted gap between conductor surface and insulator is 0.065 mm in average. This value is consistent with the requirement for the accuracy of the coil package of +2 mm and the design upper limit of the stress of 100 MPa, corresponding to a magnetic force on the helical conductor of 1,000 ton/m.

The smallest poloidal coils [inner vertical coil (IV), R = 1.8 m] and the second largest poloidal coils [inner shaping coil (IS), R=2.82 m] have been already completed and transported to the Institute. A new forced-flow, helium-cooled NbTi CIC conductor has been developed to reduce the AC loss during the plasma experiments. We have performed cool down and current excitation tests using one of the IV coils to establish a clear view of the dynamic range of the coil operation and to get the necessary control data for the LHD SC magnet.

Thus, the major activities of the LHD construction have already moved to the new site. We will proceed to the next step of the construction schedule, namely executing the difficult site-construction tasks. New directions and further progress are expected to appear during the ensuing several years of the LHD project.

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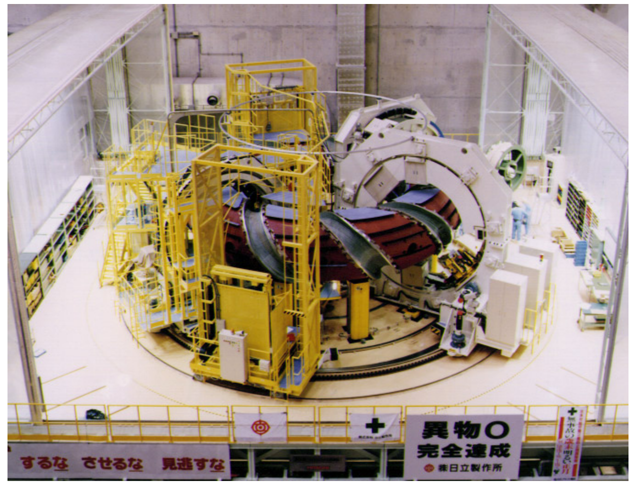

Fig. 6. The LHD helical coil winding machine.

Table 3. Requirements for the LHD helical coil.

(1) Fabrication error allotted for positioning coils	< 2 mm
(2) Surface fraction of conductors disposed to He satisfying the fully stabilized condition	30% ~ 70%
(3) Displacement of conductors by magnetic force	< 3.25 mm
(4) Stress on conductors	< 300 MPa
(5) Averaged gap between conductors and insulating spacers	< 0.0625 mm

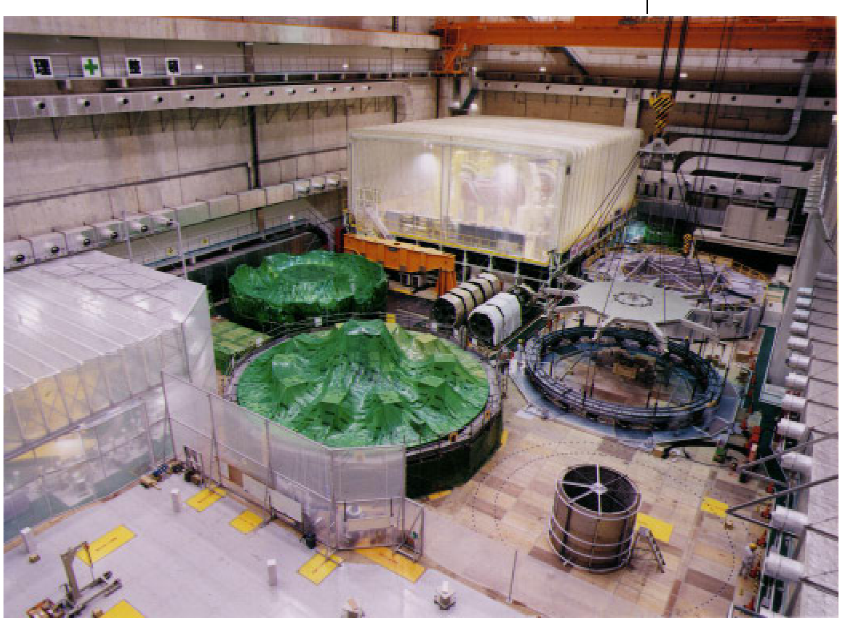

Fig. 5. An interior view of the LHD main experimental hall. The plastic-covered area at the rear is the clean room for the HF coil winding, and the one at the front-left is for the PF coil winding. The green sheet at the center of the picture covers the base support at the final LHD position. The structure at right-center is the lower half of the mechanical support assembly.

HSX construction status

The Helically Symmetric eXperiment (HSX) is a modular stellarator experiment being constructed at the University of Wisconsin-Madison Torsatron Stellarator Laboratory. The device is designed as a test of improved confinement based upon quasi-helical symmetry in the magnetic field spectrum. The toroidal curvature component is reduced to that of a “classical” stellarator with an aspect ratio of ~ 300 (although the device has a physical aspect ratio of ~8; R = 1.2 m, $\langle r \rangle$ ~ 0.15 m, B = 1T), resulting in the virtual elimination of all superbanana and direct loss orbits. The HELIAS techniques pioneered at IPP Garching have been utilized to derive the configuration and coil set. Device and conceptual design details and the proposed physics program were presented in a past *Stellarator News* article (Issue 29, September 1993). This article focuses on the engineering and construction status.

Fig. 1 shows an isometric view of the device with some drawing layers turned off to present clear views of the plasma, vacuum vessel, main coils and supporting structure.

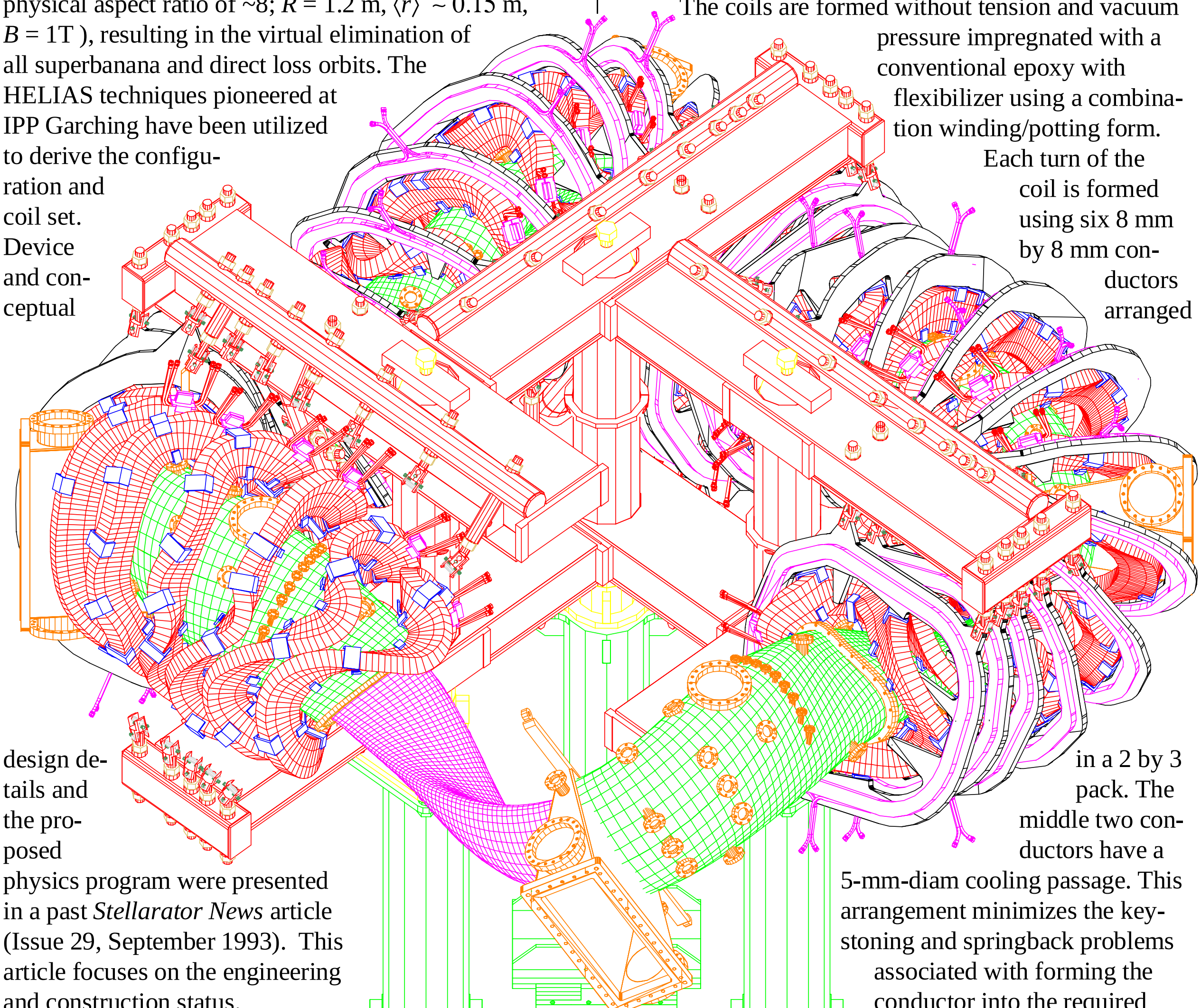

Fig. 1. The HSX device.

Modular Coil Set

The HSX field structure is attained through a set of 48 modular coils arranged into four field periods. There are six distinct types of coils in the set. The coils have a nominal cross-section of 129 mm by 56 mm, comprised of 14 turns arranged in a double pancake. The coils possess a significant degree of torsion and curvature, which were required to generate the desired field structure with a finite coil-pack size. The coils carry a current of 10.7 kA for 1-T operation.

The coils are formed without tension and vacuum pressure impregnated with a conventional epoxy with flexibilizer using a combination winding/potting form. Each turn of the coil is formed using six 8 mm by 8 mm conductors arranged in a 2 by 3 pack. The middle two conductors have a 5-mm-diam cooling passage. This arrangement minimizes the keystoning and springback problems associated with forming the conductor into the required coil shape (minimum radius of curvature about four times the conductor size). To promote epoxy bonding to the copper, each conductor is primed immediately after cleaning with Dexter Hysol EA9210H corrosion inhibitor and cured at 250° F for 1 h Each conductor within a turn is overwrapped with a

0.005-in. butt-lapped fiberglass tape to reinforce any voids between conductors. The six-conductor turn is overwrapped with a 0.01-in. half-lapped kevlar weave tape to provide the main turn-to-turn insulation. The strength of the kevlar prevents cutting of this insulation during the forming process. Brass feed blocks are resistance brazed to the conductors, and the whole (still clamped) structure is potted. The coil is removed; ground wrap is applied, and it is repotted. Kevlar cordage is applied through wet lay-up techniques to reinforce the current feed area after the final pot.

With the designed support structure, the coil stresses at B = 1.37-T operation (maximum design field) are all below 27 MPa. Material tests using the manufacturing process show epoxy/copper shear strengths in the 40-MPa range. Two production lines will be used to deliver the complete coil set by June 1996. The first winding/potting form is nearing completion, and all materials are on hand to start production.

Auxiliary Coils

A set of 48 planar trim coils provides HSX with the experimental flexibility to address many issues of the physics program. These coils allow the configuration to be varied from that similar to a conventional stellarator to that better than an equivalent tokamak with respect to neoclassical transport. The ten-turn (five turn-double pancake) coils will be mounted on the modular-coil support rings (described below) to form a modular unit with no significant decrease of experimental access over the main coil set alone. These coils carry 10% of the ampere-turns of the main modular coils. The coils are planar with all positive curvature, so they can be wound using completely conventional coil winding techniques. The same conductor is used for the trim coils as for the main coil set.

Support Structure

The major support components have been successfully bid and are being fabricated with delivery scheduled for this July. Stress levels for the coils have now been reduced to under 27-MPa peak stress intensity at 1.37-T loading. This translates to a safety factor of 3 under nominal 1-T operation without taking into account any work-hardening of the copper in the forming process. Maximum coil deflection under 1.37 T loads is 0.36 mm, or ~ 0.2 mm under design operating conditions (1 T). These levels are well below those needed from the physics design requirements (0.5 mm). The support structure will be preassembled in July and August. In addition to assembly checks, the structure can be prealigned, minimizing alignment work necessary when the completed coil/ring modules are installed on site. The support structure will also be used as an assembly jig for the vacuum.

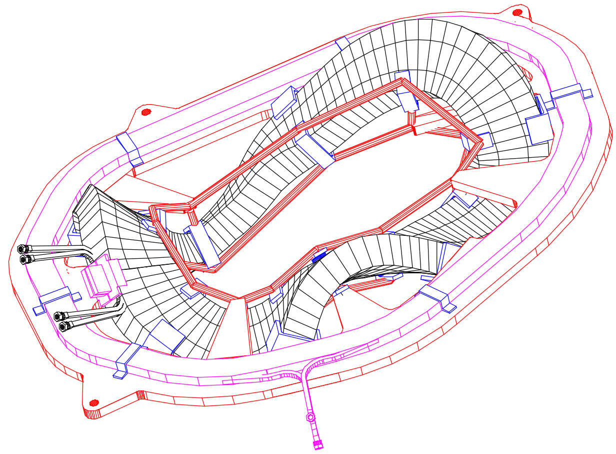

Fig. 2. An assembled HSX ring and coil module.

The main supporting structure is a series of box-beam weldments that are assembled into field-period modules. Each field period is retractable along a set of major radial guides for assembly and access to the vacuum vessel interior. Each period is completely adjustable in all six degrees of freedom (3 translational; 3 rotational) for alignment of the period modules. The box-beam field period structures are supported off of a set of four (one per period) double-column support frames that carry the machine load to grade and are part of the positioning mechanism.

The coil modules (main and auxiliary) are mounted into a set of 0.75-in. stainless steel rings that encircle the "median" plane of the coils. Figure 2 shows an assembled ring and coil module. The main coils are attached to the ring by a series of stainless steel channels welded to the rings with epoxy shims between the channels and the actual coil surfaces. The rings extend minor radially in the crooks of the coils as shown to provide support points on the interior of the coil packs in the planes of the rings. This internal support was successful in reducing the coil stress to very comfortable levels. The ring stresses, computed to be ~100 MPa under full-field operation, are well below the yield of stainless steel. The auxiliary coils are mounted to the rings with a simple bracketing arrangement, bolted on using stud welding techniques.

The rings are mounted to the central box-beam structure using a set of three "coil adjusters" per ring. Each ring has three precision holes machined into its outside edges at strategic locations to accept pins from the adjusters. The adjusters permit a ± 0.375-in. motion in all directions for coil alignment. The adjusters are placed so that each ring has an adjuster in line with the major translational force acting on that coil/ring pair.

The final element in the support structure is a set of "rigs" that tie the coil support rings together into a toroidal trusslike structure. These rigs are not shown in Fig. 1. These rigs between rings are necessary to add stability to the total structure and take some of the centering force off of the central adjusters by taking it up in compression around the torus. HSX can operate safely without any rigging at the 5-kG level. The magnetic surfaces will be mapped, with alignment and deflection modeling confirmed, before the final installation and locking down of the ring-to-ring rigs.

Vacuum Vessel and Assembly

The HSX vacuum vessel will be explosively formed. The mold rings, which define the shape of the vessel, are in fabrication. The rough pieces have all been cut, heat-treated, and blanchard ground. Machining is in progress with expected completion by June 1. The containment cylinder (a 6-in. thick "can" to hold the pieces together during the forming explosion) has been received from the forge and is being final machined. Forming will start with delivery of the mold rings in June and vessel sections will be delivered as formed for installation of porting. The forming operation is scheduled to be completed in September.

The vessel will be formed from nominally 5/16-in. type 304 stainless steel in 1/8 torus sections. Finite-element analysis gives a safety factor of 6 to atmospheric and magnetic loads. The vessel sections have demountable joints in the middle of the "straight" sections of the field period. These are custom flanges to permit installation within the coil bore volume, and their design is complete. At the "corners" of the field period, a large box-like structure (termed the "box-port") provides the greatest access to the plasma. The box port is mounted directly off of the box-beam assembly using the same adjuster design as that for the coil support ring connections. This allows the box port to be precisely positioned at assembly and supported independently from the coil set. A prototype box port is nearing completion. The vessel sections are joined to the box ports in a cut-to-fit operation that allows correction of any minor imperfections in the forming and positioning of the vessel sections with respect to the main supporting framework and coils. With this arrangement, an entire quadrant on the machine can be retracted to permit access to the interior of the vessel in the straight sections and for assembly.

The major porting layouts are near completion. The majority of the ports have standard 2 .75-in. conflat flanges (CFF) with eight 6- by 8-in. CFF and four 9-chord arrays of mini-flanges in addition to the access at the box ports. The ports are all such that the coils can be installed over the tubulations so that the entire vessel can be ported, assembled and leak-checked prior to coil installation. The box ports have 2.75-in. CFF through-views of the plasma (passing through the magnetic axis) and two 6-in. access ports on the top and bottom. The entire outer face of the box port is flanged to allow access to the vessel interior in this region and the installation of subsequent special-design portings.

The assembly sequence has the entire support structure preassembled and aligned. The joint flanges are fixed in their final positions relative to the supporting structure. The vacuum vessel is placed in its final position using the coil support rings and joint flanges as fixtures. The vessel is measured at the location of the box port wall for trimming as well as final contour cutting of the box-port wall. The entire torus, as an assembly, is stitch-welded from the fit-up positions before making the vacuum-tight fusion welds. The weldments are designed to minimize drawing and distortion.

The modular and auxiliary coils are installed in the support rings to form the completed modules as coils are delivered. The support frame and box-beam assemblies are installed on-site in their retracted positions. The vacuum vessel is installed. The coil delivery sequence and module assembly is such that modules are installed from the boxports out within each period. This allows the entire machine to be completed within a relatively short time after the last coil delivery and acceptance.

ECH and Magnet Power Systems

HSX will be initially heated with ECH using a 200-kW, 100-ms, 28-GHz Varian tube on loan from ORNL. Using LHD scaling, this should provide plasmas of ~700–1000 eV at line averaged densities of 6×10^{12} cm^{-3}. The ECH power supplies (capacitor bank and modulator, beam magnet supplies) are on loan from LLNL and have been moved to Wisconsin. The magnet power is to be provided by a set of 16 dc traction motor/generators obtained from LANL. These have been moved to Wisconsin and tested up to required speed and discharge characteristics. The power supplies to drive the armature and field windings have also been obtained from LLNL. The machine is scheduled to begin operations in August 1996.

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Engineering aspects of W7-X

Wendelstein 7-X (W7-X) uses a HELical Advanced Stellarator (HELIAS) configuration, which is optimized to achieve simultaneously seven important criteria for stellarator confinement of reactor-grade plasmas: smooth magnetic surfaces without significant islands in the confinement region, good finite-β equilibrium and stability properties, small (neoclassical) losses in the long mean free path regime, small bootstrap currents, good α-particle confinement at finite b values (in the corresponding reactor) and good modular coil feasibility. The purpose of W7-X is to demonstrate the fusion reactor relevance of HELIAS fields in a relevant plasma regime. The predicted plasma parameters of various scenarios are peak electron temperatures up to 10 keV using electron cyclotron resonance heating (ECRH) at low density of $0.1 \times 10^{20}\ m^{-3}$, densities up to $3 \times 10^{20}\ m^{-3}$ with neutral beam injection (NBI), and β up to 5%.

Figure 1 shows the W 7-X device with its main components. A total of 50 nonplanar modular coils with identical currents of 1.8 MA-turns produce the engineering standard configuration with 3-T on axis. Central and edge values of the rotational transform are 0.84 and 1, respectively. The stored magnetic energy is 0.6 GJ. There are 5 pairs of identical coils in five toroidal periods. The modular coil system is embraced by a second auxiliary set of 20 planar coils. Different currents in the modular coils and the use of the auxiliary coils provide a wide range of magnetic characteristics with different values of rotational transform, shear, magnetic well, and mirror ratio. The coils in both systems are superconducting and use a cable-in-conduit NbTi conductor with an aluminum-alloy jacket, see Fig. 2. The winding technique is similar to that of the W 7-AS coils. Conductor samples and planar test coils have been investigated; a full-size demonstration coil is under construction. These tests are performed at KfK Karlsruhe, Germany, using the STAR or TOSKA facilities to produce the background fields, with the Euratom LCT coil in the latter case, as shown in Fig. 3.

The electromagnetic forces acting on the coils of W 7-X have a helical structure. The maximum net coil force is 3.6 MN. Detailed finite-element calculations were performed to establish stresses and strains in the coil winding packs and the support system that consists of stainless steel coil housings and an intercoil support structure (Fig. 4). The latter is being optimized to

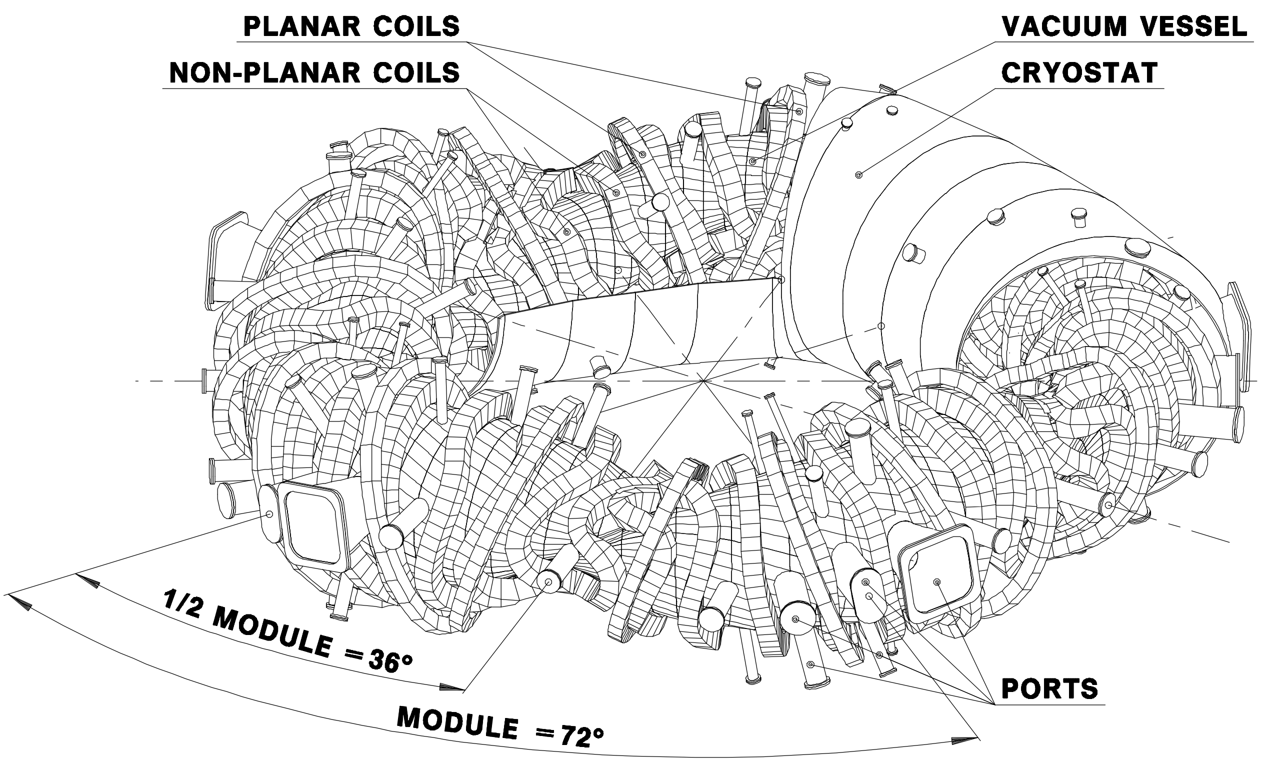

Fig. 1. Wendelstein 7-X, with R = 5.5 m, a = 0.5 m, and B = 2.5 T.

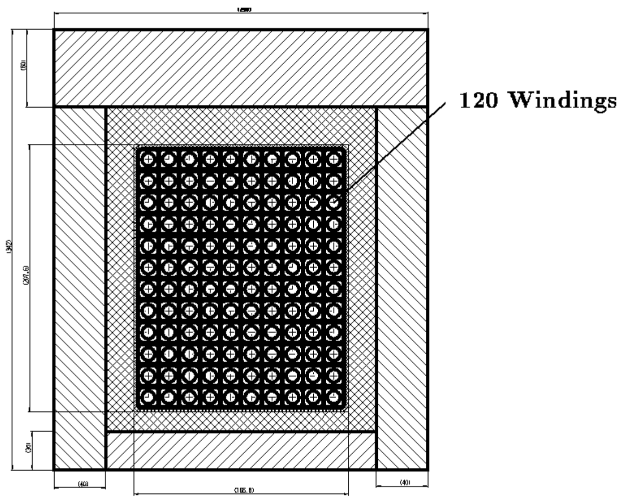

Fig. 2. Winding pack cross section of modular field coils for W 7-X. The cross-hatched area is a system of paddings between the winding pack and the coil housing.

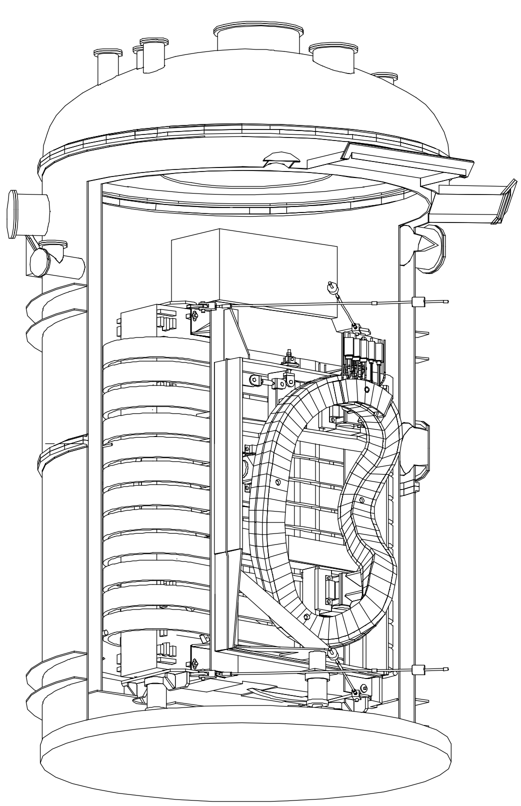

Fig. 3. TOSKA test arrangement, with EURATOM LCT coil serving as background field for test of the demonstration coil of W7-X.

reduce its mass. The complete cold mass currently amounts to about 400 tons. Cooldown times of 1 week are estimated from room temperature to 80 K and another week down to 4 K. A refrigerator power of about 6 kW is projected for W7-X. The superconducting coils are embedded in a modular cryostat. Its inner surface serves as vacuum vessel for the plasma. The fabrication will be similar to that of the vacuum vessel for W 7-AS. The 3-D surfaces of the vessel are approximated by a large number of planar surfaces on 20 toroidal segments per field period (Fig. 5). These segments are cut from stainless steel sheets, bent at prescribed angles and welded. A full-size prototype sector of the cryostat (Fig. 6), will be constructed that covers more than half of a field period to test module joints. Dummy coils serve to demonstrate the assembly procedure of this cryostat with its ports, as shown in the lower part of the figure.

Plasma heating in W 7-X will be developed in two stages. ECRH at 140 GHz with a power of 10 MW cw (10 gyrotrons) will provide plasma startup and heating up to densities of about $1 \times 10^{20}\ m^{-3}$ at a field of 2.5 T. The technical concept of the ECRH system is depicted in Fig. 7, showing half of the modular optical launcher

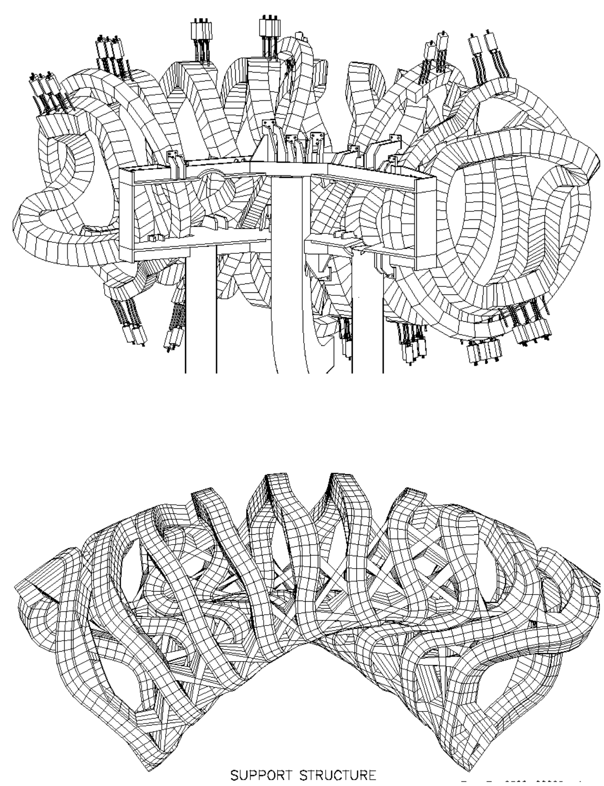

Fig. 4. Coil Support structure of W7-X (upper part) and modeling with finite elements (lower part).

design. The ports A1, E1, and N1 apply for toroidal angles of 0° (the “bean-shaped” cross section of W7-X), 8°, and 21°, respectively. Two A-ports will be used for initial operation with 6-MW ECRH power. The completion of the 10-MW ECRH system is foreseen for the subsequent year.

For NBI, one out of four plug in neutral injectors per beam line will be realized in the first stage of experimentation to provide a total power of 5 MW for 10-s pulse time with two balanced beams. Figure 8 is a sketch of the neutral beam injection geometry. ICRH will be limited in the first experimental phase to 4 MW, using existing generators with 30 to 120 MHz to develop suitable antennas and heating scenarios. Figure 9 shows the design of a double-loop antenna that is closely matched to the magnetic surfaces at the edge. The figure identifies also the port location of the two previous figures. In the second stage of experimentation, NBI will be upgraded to 20 MW at 10 s, and ICRH to 12 MW. This equipment will allow exploration of beta limits and high-power divertor operation.

Divertor development and edge plasma studies are essential items in the experimental program in W7-X. Two helically shaped divertor modules are envisaged in each field period (see Fig. 10). The wall of the vacuum vessel and the divertor target plates are designed for stationary removal of the full ECRH power. The shape of the target and baffle plates was determined from two 3-D codes: field line tracing with random offsets (Fig. 11) to model an effective particle diffusion coefficient of typically 1 m^2/s, and a neutral particle code that uses the deposition pattern at the plates as input to calculate atom and molecule densities as well as ionization rates for given plasma parameters in the interaction region.

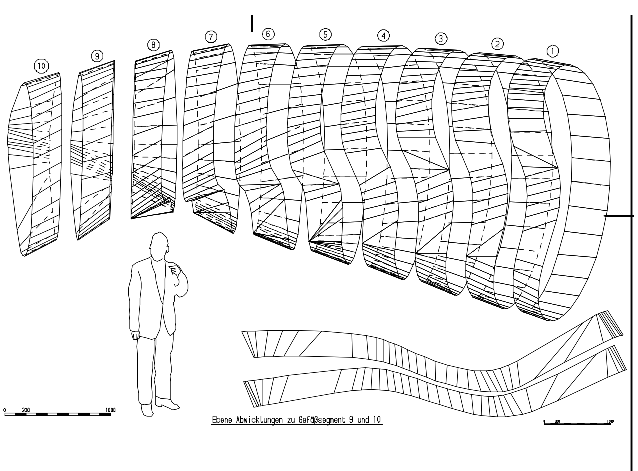

Fig. 5. Design principle of the outer and inner vacuum vessel for the W7-X cryostat.

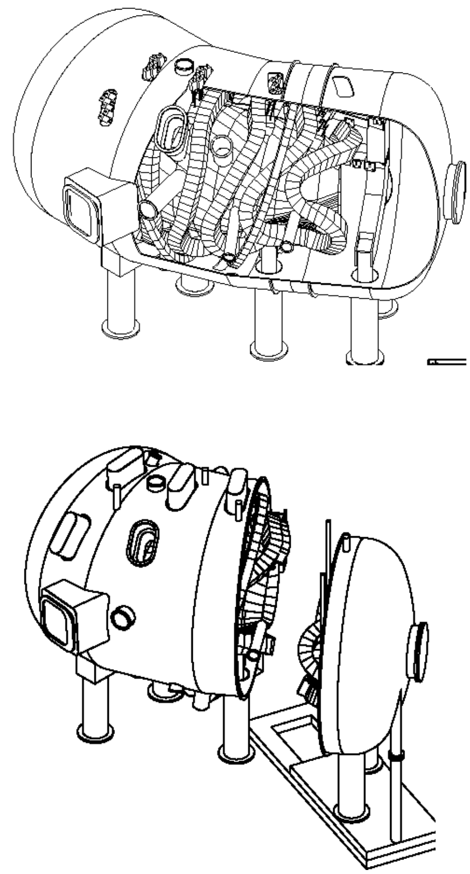

Fig. 6. Prototype vessel for the W7-X cryostat with dummy coils (top part) and demonstration of assembly by a radial shift of coils (bottom part).

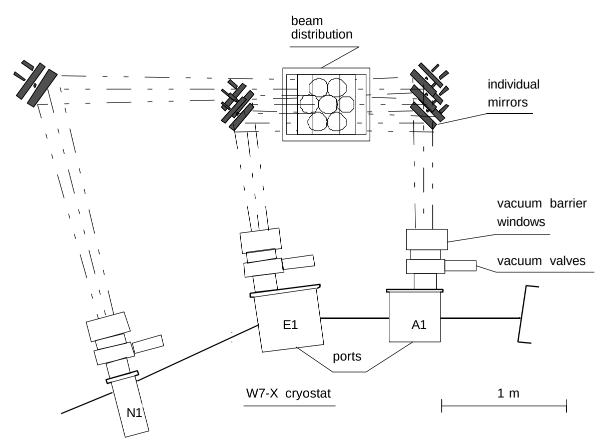

Fig. 7. Layout of ECRH launcher system, one of two modular systems. For geometrical details see following figures.

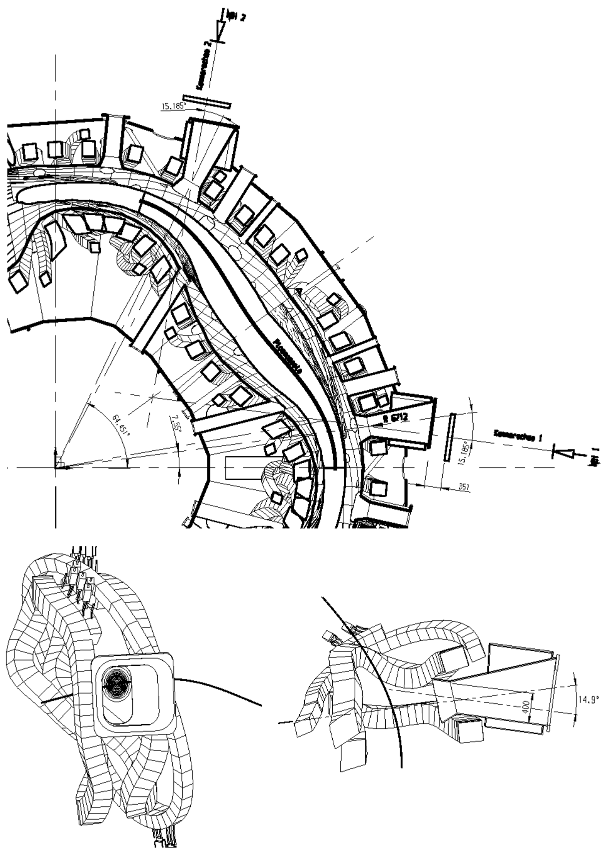

Fig. 8. Sketch of neutral beam heating geometry for W7-X.

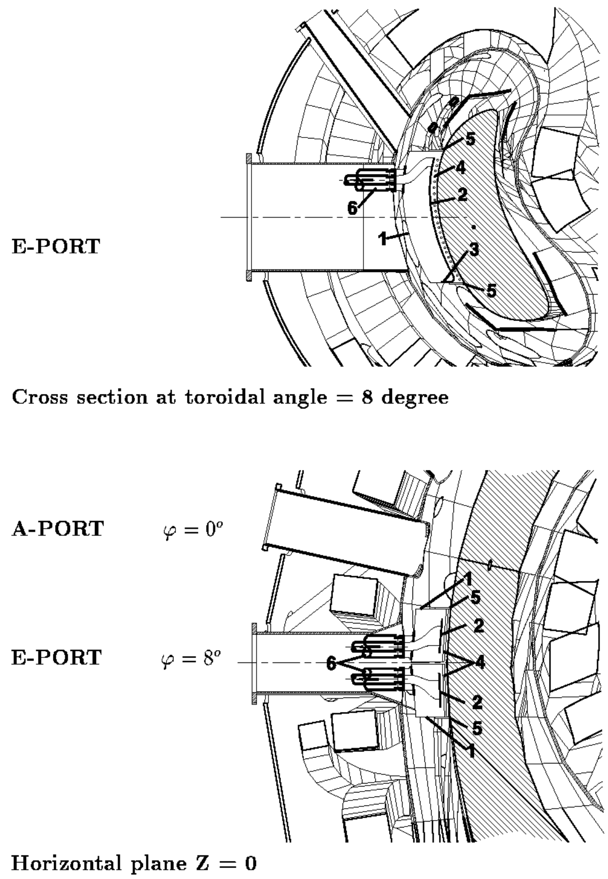

Fig. 9. Experimental ICRH antenna system for W7-X.

Power loads at the target plates are below 10 MW/m^2 (see Fig. 12); “leading edges” are avoided for the whole iota-range. Neutral particle fluxes of $\Gamma \sim 10^{23}$/s are estimated; pumping efficiencies are sufficient for stationary operation. Fig. 13 demonstrates the effectiveness of the baffle plates to reduce the neutral density outside the divertor chamber.

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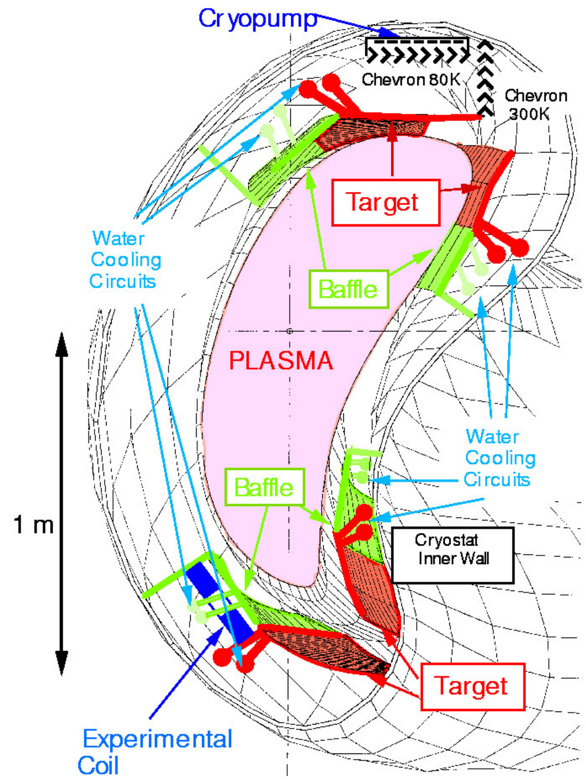


Fig. 10. (right) Divertor design of W 7-X, showing the three-dimensional structure of plasma, divertor components, and inner cryostat wall.

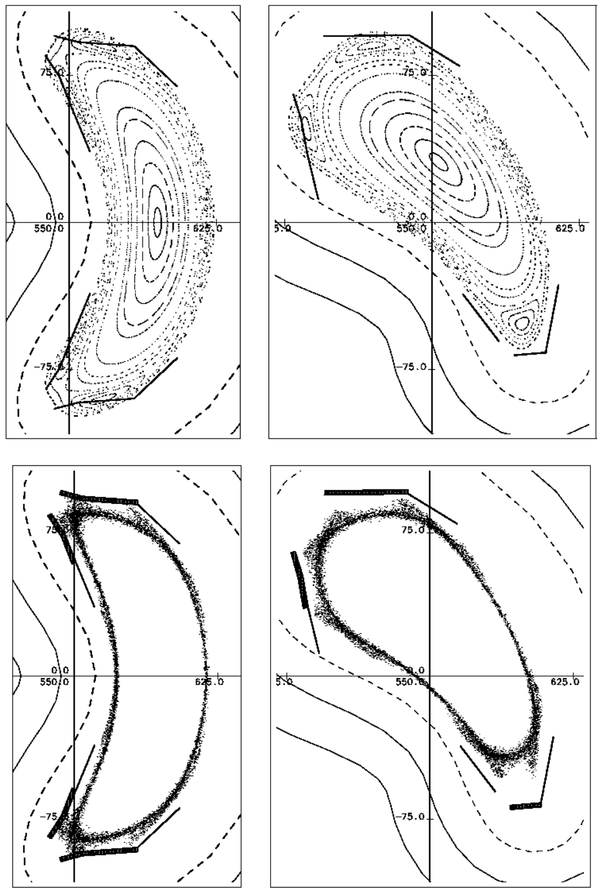


Fig. 11. Magnetic surfaces of W 7-X, showing the cross sections at toroidal angles of 0° and 18° in the top part and Monte Carlo simulation of diffusive broadening in the boundary layer in the bottom part. The diffusion coefficient is $D = 1\ m^2/s$. Target plates are indicated by bold lines; baffle plates are shown by thin solid lines.

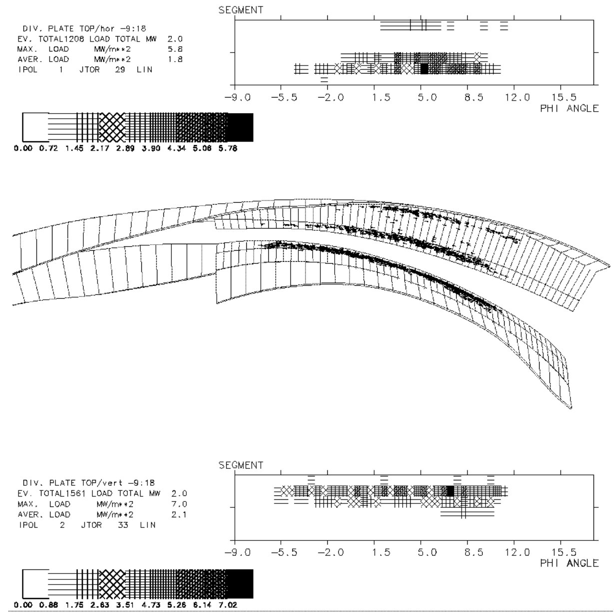


Fig. 12. Local power deposition at the target area with maximum power loads of 8 MW/m^2 for the standard case of W7-X for an input power of 10 MW. Other field topologies at W7-X yield similar values at different intersection patterns; "leading" edges are avoided.

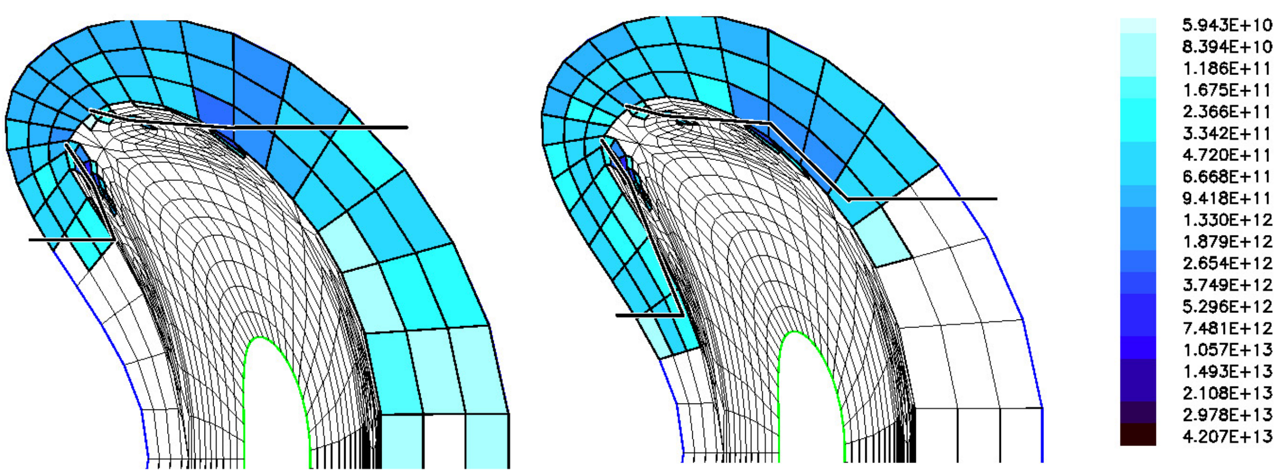


Fig. 13. EIRENE Code results demonstrating the reduction of neutral density in the region outside the divertor chamber by additional baffle plates.

Status of the TJ-II project

The flexible Heliac TJ-II is a medium size device (R = 1.5 m, $\langle a \rangle$ = 0.2 m, $B(0)$ = 1.0 T) in an advanced stage of construction at Centro de Investigaciones Energéticas MedioAmbientales y Tecnológicas (CIEMAT), Madrid. The problems encountered during manufacturing so far have been solved satisfactorily. Nevertheless the narrow tolerances, which result from the compact machine design, create real challenges for all the component manufacturers. In this paper we present the present status of the project with a particular emphasis on the construction of the main components.

INTRODUCTION

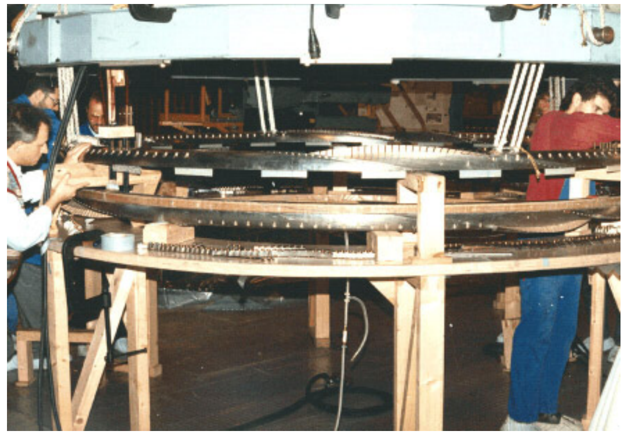
TJ-II coil configuration consists of 32 toroidal field coils centered around a toroidal helix of major radius R_0 = 1.5 m, minor radius r_{sw} = 0.28 m, and pitch law $\theta = -4\varphi$, where θ and φ are the usual poloidal and toroidal angles [1]. The flexible heliac owes its name to the central conductor ("hard core") that is made of two components, a circular coil (CC) located at the major axis, 1.5 m, and a helical winding (HX) wrapped around the circular one following the same winding law as the toroidal coils. These separately controllable currents in the central conductor windings give the device its unique flexibility, which is characterized by a wide range of attainable physical parameters ($0.96 < ɫ_0 < 2.5$, –1% < Mag. Well < 6%) that can be independently controlled and differentiate it from the original heliac design. Two circular vertical field coils complete the coil configuration.

The design phase of TJ-II, which terminated in June 1990, was followed by a design review phase that was finished toward the middle of 1991. Overlapping with the design review and continuing after its termination, the specifications were prepared and the tendering actions for the main components were started; contract placing and construction followed.

STATUS OF DIFFERENT COMPONENTS

Hard Core

The manufacturing contract was placed with Noell of Würzburg, Germany, in middle of 1992. Delivery of this component to Madrid is scheduled for June 1995. This means a delay of 4 months, which has primarily been caused by necessary additional machining of the casing and its elements. The CC coil was assembled into the casing in the middle of April 1994. In May a full current test has been successfully conducted at IPP in Garching, Germany. The reason for this test was to guarantee a faultless operation of the CC coil before winding the HX coils over it, because no access is possible to this coil afterward. The winding device for the HX coils was completed in March 1995. A test winding on a full-scale dummy has been terminated. An additional test winding will be done on the hard core casing with the final copper profile of the HX coil still this year. To check the precise position of the HX base surface on the casing, an optical high-precision measurement was performed in Garching in May. The results have been satisfactory although minor deviations from the ideal geometry have been found mainly in the flange area.

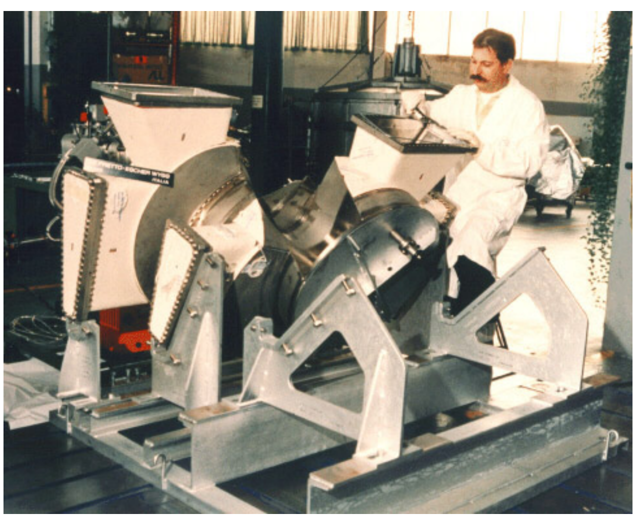


The CC coil is shown in the lower half of the hard core casing shortly before being joined to the upper half of the casing. The helically machined surface is the form for the helical coils to be wound later.

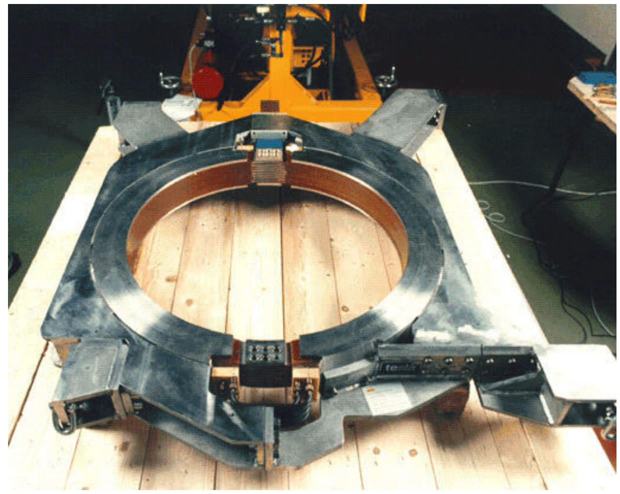
Vacuum Vessel

The contract for the manufacturing of the vacuum vessel was placed with De Pretto of Schio, Italy, in October 1991. The contractual manufacturing time has been 28 months. Delivery of the vacuum vessel is now scheduled for the middle of 1995. Tolerance problems have been solved by optimizing the welding cycles and by improving the manufacturing devices. The heat treatment of the vacuum vessel subassemblies, necessary to relieve internal stresses, is done at 950°C in an inert atmosphere. Nevertheless some oxidation of the surface of the vacuum vessel has been observed. A pickling process and a subsequent mechanical grinding of the entire inner surface provide a surface quality that complies with the ultra high vacuum requirements as detailed electron microscopic and other investigations by CIEMAT have demonstrated. The first series octant has been ready for the vacuum test since the beginning of September 1994. A leak rate out of tolerance has been observed above 115°C. Improvement of the sealing is being done presently with the support of IPP and Sulzer. The call for tender for the vacuum pumping system was initiated in June 1994. A sufficient number of good offers had been received by the end of September. Con-

A test welding of the TJ-II vacuum vessel at the manufacturer's. Sixteen internal welds must be done to connect the eight sectors. Due to the narrow space condition, a test welding was necessary. To enter the vacuum vessel, eight ports are available, each having an aperature of 0.25 m by 0.53 m.



An octant of the vacuum vessel during fabrication showing the ports. The eight octants will be welded together.



The TJ-II TF coil in its casing and support frame. The inner coil diameter is about 0.8 m. The eight copper turns are water cooled and splitable. The stainless steel parts have a permiability of less than 1.01.

tract placement is expected to occur at the end of this year. Delivery time is about one year.

Toroidal Field Coils

The contract for the manufacturing of the toroidal field (TF) coils was placed with Tesla in Storrington, UK, in April 1992. Manufacturing time was 26 months. The first eight series coils were sent to IPP-Garching for full-current tests in August 1994; eight more coils will follow in November. All the coils will be delivered by the end of January 1995. One of the series coils has already been delivered to Madrid. This coil has passed the incoming tests successfully. Some delay has been caused due to the very careful investigation of the material used for embedding the coil into the coil casing. The embedding material must provide a stiff and safe support of the coil against the magnetic forces. Moreover it must allow the thermal expansion of the coil without creating high thermal stresses. Silcoset, the embedding material proposed by Tesla, has been finally approved. The prototype coil has been mechanically tested for 100.000 lateral full load cycles without any damage.

Poloidal Field Coils

The contract for the manufacturing for these poloidal field (PF) coils was placed at ABB in Augsburg, Germany, in March 1991. All the coils were finished on time and have successfully passed the tests at the factory and the full-current test at IPP-Garching. All the coils were delivered to Madrid at the end of October 1993. The coils are now stored in the TJ-II torus hall.

Support Structure

The manufacturing contract for the support structure has been placed with Kamfab of Karlstad, Sweden. The work on this contract was started in September 1992. The manufacturing of this structure was finished in February 1994 according to schedule. The load tests have shown the expected deformations. To check the dimensional control of Kamfab, Leica of France has done a comprehensive dimensional control of the entire support structure in Karlstad, Sweden together with CIEMAT. In the critical areas the measurements of Kamfab and Leica show good agreement. In some areas deviations of up to 3 mm exist from the ideal geometry. These deviations have been reduced by shimming during the assembly in Madrid to acceptable 1.5 mm. This assembly in Madrid was done by Kamfab and CIEMAT by the end of September 1994. The entire structure was assembled within 1 week. All the tests done prior and during manufacturing, especially the test of the magnetic permeability, have successfully been passed.

Power Supply

The main components of the power supply system are a motor generator set and the thyristor converters, which supply the magnetic field coils. In addition to the seven coil systems, the generator must also power the auxiliary heating systems (ECH, NBI, ICH?). The generator output data are: 15 kV, 130 MVA, and 100 MJ. The dc currents range from 5.2 kA in the R-coils to 32.5 kA in the TF magnet. The entire power supply system has been contracted with Jema, Spain, as a turn-key package. This means that the entire system must be calculated, designed, fabricated, installed, and commissioned by the contractor. The static calculations have already been finished. The dynamic simulations and the planning of the main components are under way.

Cooling System

This system consists of the cooling tower located on top of the roof of the experimental building and the pipes and pumps for the cooling of coils and auxiliary systems of TJ-II. The water distribution in the torus hall is not included in this specification because the detailed design of these parts is not yet finished. These components will be a matter for a separate contract. The contract was placed with Sulzer of Spain in January 1994. The work is progressing very well in accordance with the time schedule. The on-site installation will begin in November of this year. Commissioning is expected for January 1995.

Monitoring and Control

The main activities concentrate on the system definition and the selection of the hardware along with the training of the personnel. The control systems for the peripheral systems such as power supply, cooling etc. will be included in the main contracts for these systems. VME will be introduced as the general standard. A VME based timing system will be used; it has a central clock but separately programmable channels for technical control and diagnostics. The non-coded signals will be transmitted by fiber optics.

Building

The experimental building including the torus hall is already finished. The building for the power supply is time critical. Therefore our activities within the power supply contract concentrate at the moment on the final definition of this building.

HEATING

For TJ-II heating, three phases are foreseen. In the initial phase, we will install two gyrotrons working at 53.2 GHz, able to deliver at least 400 kW into the plasma in the X-mode. A considerable versatility has been introduced into the design of the quasioptical transmission line that will permit us to exploit the operational flexibility of the machine. For the second phase 2 MW of neutral beam power is envisaged that will permit us to explore the finite beta effects on Heliacs. The third foreseen phase will be implemented with an additional 2 MW of power that could come in the form of NBI or ion cyclotron resonance heating (ICRH) ,depending on experimental results from TJ-II and other stellarators.

TIME SCHEDULE

The assembly work in the torus hall was started on September 26, 1994, with the assembly of the entire support structure. This structure will be partly disassembled, and the PF coils will be mounted into the four rings of this structure. The main assembly activities on TJ-II will be done during 1995 and the first months of 1996.

Commissioning and first plasma depend on the availability of the power supply system. Taking into account the contractual delivery time of the power supply system, commissioning of TJ-II can begin in the first half of 1996.

Reference

1. C. Alejaldre, J. Alonso, J. Botija, F. Castejon et al., “TJ- II Project: A Flexible Heliac Stellarator”, *Fusion Technology*, **17**, 131 (1990).

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Fabrication of the LHD helical and poloidal coils

Superconducting helical and poloidal coils for the Large Helical Device (LHD) are now under construction. The helical coil is being wound on site using a specially made winding machine with a speed of 5 m/h. A picture of this machine is shown on page 5 of this issue. Two sets of poloidal coils, named inner vertical (IV) and inner shaping (IS), have already been produced, and the outer vertical (OV) field coils are now being wound on site. This article presents the details of the coil winding process.

Helical coil design

The helical coil is a pair of large-scale pool-boiling superconducting coils and is designed to satisfy the fully cryostabilized criterion. Table 1 shows the specification of the helical coil. The helical-coil conductor consists of Nb-Ti/Cu compacted strands, a pure aluminum stabilizer with Cu-2%Ni cladding, and a half-hard copper sheath. Its size is 12.5 mm by 18.0 mm. Because the conductors are not able to withstand the large electromagnetic force by themselves, they are designed to be packed into a thick case. Ground insulation was directly pasted on the can by autoclave method. The conductor is directly wound on the can from the bottom up, to a total of 450 turns per coil, with a total total length of 36 km. It will take 18 months to wind all of the conductors. Electrical insulators between conductors are inserted at intervals to provide a cooling channel for liquid helium. The thicknesses of the insulator between the turns and the layers are 2.0 mm and 3.5 mm, respectively. The cross section of the coil is shown in Fig. 1.

Requirement for the helical coils

Accuracy of the position of the coil is important to achieve a good magnetic configuration. The fabrication error for the position of the coil is required to be under 2 mm. This value corresponds to 5×10^{-4} of the major radius. Furthermore, the elastic deformation of the coil by electromagnetic force should be held to < 1.9 mm at 3-T operation. The helical-coil conductors are, therefore, designed to be packed into a thick can made of 316 stainless steel. Because the can plays the role of a bobbin for the helical coil, the fabrication error of the can must also be small. As a result of research and development on the welding process, fabrication error of the can was maintained under 1.5 mm. While winding, we must also keep the accuracy of relative position of the conductor to the can within 0.5 mm. The motion of the conductors due to electromagnetic forces must be small;

Table 1. Major parameters of the helical coil

Item	Phase I	Phase II
Bath temperature	~ 4.4 K	~ 1.8 K
Central toroidal Field	3 T	4 T
Maximum field in coil	6.9 T	9.2 T
Nominal current	13.0 kA	17.3 kA
Recovery current (cal.)	15.0 kA	
Current density	40 A/mm^2	53 A/mm^2
Magnetic stored energy	0.92 GJ	1.64 GJ
Voltage to earth	1181 V	1574 V
Voltage between layers	393 V	525 V
Major radius/ Minor radius	3.9 m/0.975 m	
Superconductor	Al stabilized NbTi/Cu	
Surface treatment	Oxidization	
Number of turns	450	
Size of conductor	12.5 mm × 18.0 mm	
Spacer factor	30% ~ 70%	
Spacer pitch	49.2 mm ~ 64.3 mm	

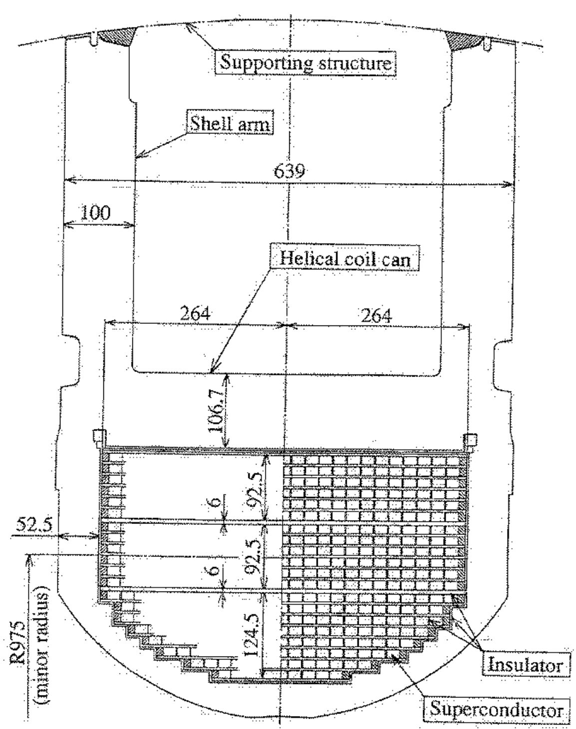

Fig. 1. Cross-section of the LHD helical coil.

that is, the rigidity of the coil must be high. We have developed a glass-fiber-reinforced plastic (GFRP) with a high rigidity. The modulus is larger than 22 GPa, and the compressive strength is over 1000 MPa. In the case of the rigidity of 22 GPa, movement of the lowest layer and the maximum stress on conductors are calculated to be 1.1 mm and 173 MPa, respectively. Since the electromagnetic force on insulator would reach 100 MPa, the fabrication gap between conductor and insulator would collapse. This means that the fabrication gap lessens the equivalent rigidity of the coil. If the stress on conductor exceeds the yield strength, plastic deformation would occur until the stress would be released under the yield strength. It is not a strict condition but a good engineering practice to keep the stress on the conductor within the elastic region. As a result of finite element modeling, the average fabrication gap should be smaller than 0.065 mm per layer to satisfy this criterion. Figure 2 shows the details of a coil package.

Method of helical coil winding

The helical-coil winding machine, with the specifications shown in Table 2, is used for shaping the conductors with high precision and feeding them tightly into the helical-coil can. This machine is unable to apply tension on the conductors because the in-plane curvature of the coil changes its direction. This tension, however, is necessary to reduce the gap between the conductors and to enhance the rigidity of the coil. We have developed a method for applying tension on the conductor by shifting it sideways in the fixing work. We can apply almost 50 MPa by shifting it 5 mm. We manage to hold the shaping error of the conductor within 10 %; the maximum gap due to the slant of each conductor is within 0.30 mm, and the average gap due to the slant is within 0.13 mm. In addition, we fuse reinforced epoxy resin to fill between the top of the conductor and the bottom of the layer-to-layer insulator. The resin is cured at room temperature, and the compressive modulus is higher than 10 GPa which is about one-half as much as that of the insulator. The gap under the conductors remains, but the effective residual gap is considered to be half of the fabrication gap caused by slanting.

Coil design and requirement for the poloidal coils

The maximum allowable error field of the poloidal coils should be 4 gauss at the plasma center, at the maximum field of 4 T. Several operation modes require the time variation of electromotive force. The base case is to change the magnetic field change in 5 s during the 300-s operation period. The fastest field change is 0.5 T/s at the conductor. We have chosen to fabricate the coil

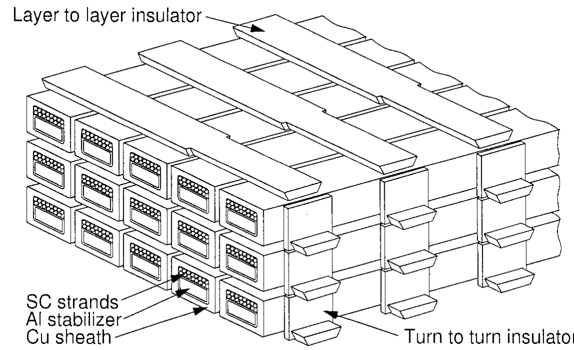

Fig. 2. The assembly of the helical coil components.

Table 2. Specifications of the LHD winding machine

Size of center stage	13.1 m × 3.6 m(H)
Size of working floor	24.2 m × 27.7 m
Height of clean room	12.4 m
Total weight	280 ton
Work weight	320 ton
Toroidal rotating speed	0.1 rpm.
Load on a up-down support	180 ton
Length of a conductor	1,200 m
Number of NC axes	13
Range of shaping conductors:	
out-plane bending	5.8~7.0 × 10-4 /mm
in-plane bending	3.1 ~ 3.110-4 /mm
torsion	3.4 ~ 7.7 × 10^{-4} rad/mm

structure from stacks of double pancakes with a Nb-Ti cable-in-conduit type conductor. Main parameters of coil are tabulated in Table 3. Mechanical force is transferred to the electromagnetic support shell of LHD, when the displacement of the coil is limited to 3.4 mm at the full operational conditions. However, the coil can be energized at full current without any mechanical support due to the elasticity of the coil itself. All coils are cooled by forced-flow supercritical pressurized helium (1 MPa at 4.5 K) passing through the parallel 16 pancake conduits and supporting sleeves (PC sleeves). High stability is the most important design policy of the conductor. The cable-in-conduit conductor is made of 6 by 34 multi-NbTi superconducting strands. The conduit is 23.0 by 27.6 mm with 3-mm thickness for IV and IS coils, and 27.5 by

31 mm with 3.5-mm thickness. The strand is made of simple copper-stabilized multifilaments without surface insulation as shown in Table 4.

Construction of poloidal coils

Each coil is a molded structure of eight double pancakes with fan-shaped “PC sleeves” made of stainless steel. Figure 3 shows the view of the IS coil. The sleeves not only hold the coils to a supporting shell, which is also connected to the helical coils, but also cool the coil indirectly to near room temperature because of the large pressure drop through the conduit. At the winding stage, the conduit is wrapped with 0.5-mm-thick glass polyimide epoxy prepreg tape. The 0.5-mm-thick spacers are also inserted between pancakes to assure electrical insulation of 3 kV. The total insulation thickness is, therefore 1 mm between turns and 1.5 mm between layers as shown in Fig. 4. To minimize the error field, the pancakes after molding keep tolerance of 2 mm for the inner and outer diameters and 1 mm for the height. The tolerances correspond to extreme accuracy of about 5×10^{-4} for the diameter. All pancakes are inspected regarding the dimension, resistance, inductance, insulation capacity, helium leak, pressure resistant capacity, and pressure drop. The pancakes are then stacked and molded. The electric joints between pancakes were arranged outside the coil to reduce the error field. The conductors are jointed superconductively by using a solid state bonding technique between Nb-Ti filaments not only to decrease ohmic loss but also to reduce the error field depending on its size. If we adopt the conventional solder joint, the error field is estimated five times larger than that by the present

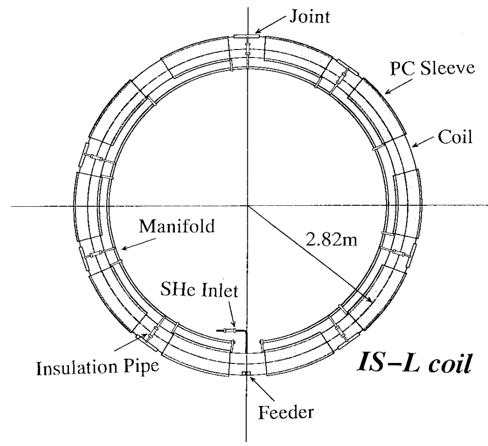

Fig. 3. A top view of the lower inner shaping coil.

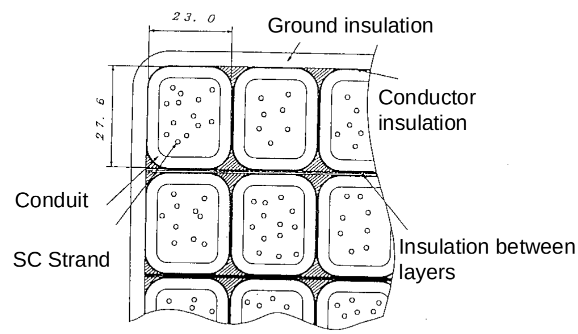

Fig. 4. Details of the poloidal coil construction and electrical insulation.

Table 3. Main parameters of poloidal coils

	IV	IS	OV C
Cooling type	Forced-flow		
Inner/outer radii[a] (m)	1.6/2.1	2.7/3.1	5.4/5.8
Height[a] (m)	0.46	0.46	0.54
Total weight[b] (tons)	16	25	45
Number of pancakes[b]	16	16	16
Number of turns[b]	15×16=240	13×16=208	9×16=144
Operating current (kA)	20.8	21.6	31.3
Maximum field (T)	6.5	5.4	5.0
Stored energy[b] (MJ)	68	104	251

[a] including an earth insulation [b] per coil

Table 4. Principal specifications of conductors for the LHD poloidal coils

Poloidal coils	**IV**	**IS**	**OV**
Type	Cable-in-conduit	Cable-in-conduit	Cable-in-conduit
Superconducting material	Nb-Ti	Nb-Ti	Nb-Ti
Conduit dimension (mm)	23.0×27.6	23.0×27.6	27.5×31.8
Thickness (mm)	3.0	3.0	3.5
Void fraction (%)	38	38	38
Strand diameter (mm)	0.76	0.76	0.89
Number of strands	486	486	486
Nb-Ti:Cu	1:2.7	1:3.4	1:4.3
Strand surface	Bare	Bare	Bare

technique because of the large contact area and the space for soldering. Required space for the joint is only 37 mm wide, 50 mm high, and 60 mm long. Critical current of the joint is less than the original conductor value, but still about two times larger than the operational point. Ground insulation of 4-mm-thickness is wound around the molded coil. Finally the coil is covered with PC sleeves.

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